Regional Wave Attenuation and the Lg/P Discriminant

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Contract No. F19628-95-C-0097
Sponsored by U.S. Department of Energy

ABSTRACT

Results from previous empirical studies indicate that the high-frequency Lg/P ratio is one of the most promising discriminants at regional distances. However, many of these studies are based on co-located earthquakes and explosions in limited geographic regions, and their results must be recalibrated for each new source region. We just started a two-year research project to develop frequency-dependent attenuation models for regional phases and to use them to generalize the high-frequency Lg/P discriminant for use in uncalibrated source regions.We plan to develop attenuation models for up to 10 primary (or Alpha) stations from the Group of Scientific Experts Technical Test (GSETT-3). These models will be used to normalize frequency-dependent Lg/P amplitude ratios for thousands of events recorded during GSETT-3 to a common reference distance. We will develop discriminants based on these distance-corrected ratios, and we will evaluate their effectiveness and limitations (including the sensitivity to the accuracy of the attenuation models). We will obtain *ground-truth* identification for as many of the events as possible, and we will use knowledge of the local natural and industrial seismicity to qualitatively evaluate effectiveness when this information is not available. We will attempt to generalize the distance-corrected Lg/P ratio by geological and tectonic environment so that this discriminant can be extrapolated with confidence to uncalibrated regions.

KEY WORDS: Generalized Inversion, GSETT-3, Regional Discrimination, Regional Wave Attenuation, Regionalization, Software Development, Transportability

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INTRODUCTION

Results from previous empirical studies indicate that the high-frequency Lg/P ratio is one of the most promising discriminants at regional distances. However, many of these studies are based on co-located earthquakes and explosions in limited geographic regions, and their results must be recalibrated for each new source region. We just started a two-year research project to develop frequency-dependent attenuation models for regional phases and to use them to generalize the high-frequency Lg/P discriminant for use in uncalibrated source regions. This paper presents our research plan.

1.0 OBJECTIVE

The primary objective of this project is to develop frequency-dependent regional wave attenuation models and use them to generalize the high-frequency Lg/P discriminant. Table 1 lists the primary technical tasks.

Table 1: Task Description

Task	Description
1.0	Develop processing parameters for measuring regional wave amplitudes
2.0	Develop software for regional wave amplitude inversion
3.0	Develop regional wave attenuation models for up to 10 GSETT-3 stations
4.0	Assemble data sets for testing the Lg/P discriminant
5.0	Calculate the distance-corrected Lg/P amplitude ratios
6.0	Determine the identification accuracy of the Lg/P discriminant
7.0	Determine the sensitivity of the Lg/P discriminant to the accuracy of the attenuation models
8.0	Generalize the results in terms of geologic and tectonic environment

We plan to develop attenuation models for up to 10 primary (or Alpha) stations from the Group of Scientific Experts Technical Test (GSETT-3). These models will be used to normalize frequency-dependent Lg/P amplitude ratios for thousands of events recorded during GSETT-3 to a common

reference distance. We will develop discriminants based on these distance-corrected ratios, and we will evaluate their effectiveness and limitations (including the sensitivity to the accuracy of the attenuation models). We will obtain *ground-truth* identification for as many of the events as possible, and we will use knowledge of the local natural and industrial seismicity to qualitatively evaluate effectiveness when this information is not available. We will attempt to generalize the distance-corrected Lg/P ratio by geological and tectonic environment so that this discriminant can be extrapolated with confidence to uncalibrated regions.

2.0 PRELIMINARY RESEARCH RESULTS

We started development of software to invert frequency-dependent regional wave amplitudes for attenuation models (Task 2.0). Figure 1 shows the major software components. `DFX` was developed for the International Data Center (IDC) to perform seismic signal detection and feature extraction. It will be used in this study to compute frequency-dependent regional wave amplitudes in the time and frequency domains. `AmpInv` is a new program being developed under this contract to invert regional wave amplitudes for attenuation models.

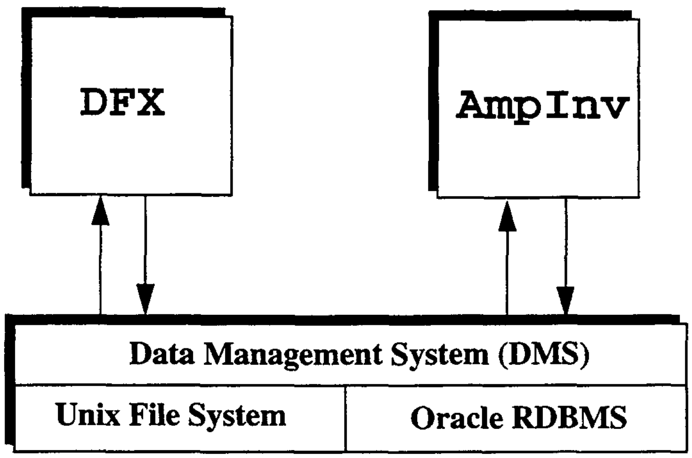

Figure 1. This shows the two major software components for the attenuation study, `DFX` and `AmpInv`. These components share a common library for access to the centralized data management system.

3.0 RECOMMENDATIONS AND FUTURE PLANS

Our plans for this two-year project are divided into two categories: (1) frequency-dependent regional wave attenuation, and (2) the Lg/P discriminant. After a brief introduction, this section describes the work to be completed in each category.

3.1 Introduction

Several early studies propose the use of Lg/P ratios as a regional event discriminant for earthquakes and nuclear explosions [e.g., *Willis et al.*, 1963; *Blandford*, 1981; *Gupta and Burnetti*, 1981; *Nuttli*, 1981; *Pomeroy et al.*, 1982; *Murphy and Bennett*, 1982; *Bennett and Murphy*, 1986; *Taylor et al.*, 1989]. These studies found that Lg/P discriminants provide some separation between nuclear explosions and earthquakes, but that there is significant overlap between the two populations. More recent studies have exploited higher frequencies to improve the Lg/P discrimi-

nant and have extended the application to include industrial chemical explosions. For example, high-frequency (2-16 Hz) Lg/P ratios have shown to be successful in discriminating between earthquakes and mining explosions in northern and central Europe [e.g., *Baumgardt and Young*, 1990; *Dysart and Pulli*, 1990; *Baumgardt et al.*, 1992; *Wuster*, 1993], and earthquakes and underground nuclear explosions in Eurasia [e.g., *Bennett et al.*, 1989; *Chan et al.*, 1990; *Bennett et al.* 1992]. The practice of mining can also induce stress-release events such as rockbursts. Often these stress-release events are much larger than the actual mining explosions. *Bennett et al.* [1993] show that stress-release events in central Europe and South Africa have similar Lg/P ratios (> 1.0) to earthquakes across broad frequency bands, and these are higher than the ratios for underground nuclear explosions (< 1.0) at frequencies above 2 Hz. Most of these studies use co-located explosions and earthquakes to minimize propagation effects. A major concern expressed in the recent research is that propagation characteristics may have a significant affect on the Lg/P discriminant, and that transportability may be problematic [e.g,. *Lynnes and Baumstark*, 1991; *Bennett et al.,* 1992]. In the next section, we describe how we propose to account for the path effects by developing frequency-dependent regional wave attenuation models.

3.2 Frequency-Dependent Regional Wave Attenuation

Amplitude Measures (Task 1.0). Frequency-dependent amplitudes will be computed automatically using DFX. We will investigate the use of both spectral and time-domain amplitude measurements. For either type, the time window will depend on which regional phase is being measured. Part of this task will be to determine the optimal time windows for P and Lg phases. We will experiment with fixed group velocity windows with respect to the estimated location and origin time of the event, and shorter, fixed-duration time windows near the arrival time of associated P and Lg phases. The time windows will be selected on the basis of the consistency of the log amplitudes with magnitudes in independent bulletins. The spectra computed by DFX will be stored in Unix ASCII files and indexed in an Oracle relational database management system (RDBMS). The time-domain amplitudes will be stored in the Oracle RDBMS.

Amplitude Inversion (Task 2.0). Our parameterization and inversion method are described in detail by *Sereno* [1990]. Briefly, the frequency-dependent (either time-domain or spectral) amplitude of the *kth* wave recorded at the *ith* station from the *jth* source is parameterized as:

$$\log A_{ijk}(f) = \log A^0_{jk}(f) + B_k(\Delta_{ij}, \Delta_0, f) + \delta_{ik} \qquad (1)$$

where $A^0_{jk}(f)$ is the amplitude at a reference distance Δ_0, $B_k(\Delta_{ij}, \Delta_0, f)$ is the attenuation from the reference distance to the epicentral distance Δ_{ij}, and δ_{ik} is a station correction. The amplitude at the reference distance is expressed in terms of the material properties at the source and the receiver, source parameters such as the seismic moment, the shape of the source spectrum, and a wave-dependent excitation factor. We use the *Mueller and Murphy* [1971] and *Brune* [1970, 1971] models to parameterize the shape of the source function.

The attenuation is parameterized in terms of a power-law distance dependence with a frequency-dependent exponent:

$$B_k(\Delta_{ij}, \Delta_0, f) = -\log e \cdot \alpha^0_k \cdot f + n_k(f) \cdot \log(\Delta_0/\Delta_{jk}) \qquad (2)$$

where the first term accounts for anelastic attenuation from the source to the reference distance, and the second term is the total attenuation from the reference distance to the epicentral distance.

The total attenuation includes geometrical spreading, scattering and anelasticity. It is difficult to separate these terms since the geometrical spreading of regional phases is a complicated function of the crustal and upper mantle velocity structure [e.g., *Sereno and Given*, 1990]. Fortunately, it is not important to separate these terms for application to the Lg/P discriminant. The exponent, $n_k(f)$, is parameterized as a linear function of frequency. *Chun et al.* [1989] used this parameterization to estimate Pn attenuation in the Canadian Shield.

Frequency-Dependent Attenuation Models (Task 3.0). This parameterization will be used to develop frequency-dependent attenuation models for regional phases recorded by up to 10 stations in the primary (or Alpha) network for GSETT-3. An example is provided by our earlier work with data from the NORESS and ARCESS arrays in Norway [*Sereno*, 1990]. We inverted frequency-dependent amplitudes of four regional phases for source scaling parameters, frequency-dependent attenuation models, and station corrections. The data set included nearly 100 events with magnitudes between 2.0 and 3.6, and epicentral distances between 200 and 1600 km. Our results for the frequency-dependent attenuation of Pn, Pg, Sn, and Lg are plotted in Figure 2. The model provides a reasonable fit to the observed data.

3.3 Lg/P Discriminant

Data Sets (Task 4.0). The data sets for testing the Lg/P discriminant will include the events used to develop the attenuation models, but they must also include others. The attenuation models are based on the highest quality data that are available. However, the Lg/P discriminant must be tested on typical events in the GSETT-3 analyst-reviewed bulletin (i.e., not just the highest-quality events). We propose to assemble two test data sets to evaluate the effectiveness of the Lg/P discriminant for each station. We will call the first one the *ground-truth* data set because it will consist of events whose identifications are known with high confidence. It will be assembled by gathering information from operators of local networks, universities, and government agencies. The second data set will include a large number of events (>1000 per station) intended to represent the type of events that must be routinely identified by a seismic monitoring system. In general, we will not have *ground-truth* information for these events. Instead, we will rely on knowledge of the local natural and industrial seismicity to qualitatively evaluate the effectiveness of the Lg/P discriminant.

We used this approach to evaluate the performance of the Event Identification System that we developed for ARPA's Intelligent Monitoring System (IMS) [*Sereno and Wahl*, 1993]. We used a local bulletin produced by the University of Helsinki as our *ground-truth* data set. The events in the Helsinki Bulletin are identified as mine blasts or earthquakes by experienced analysts based on data from a dense network of stations in northern Europe. The second data set that we used to evaluate the Event Identification System consisted of >6000 events in the IMS bulletin between November 1990 and June 1991. The results are plotted on a map in Figure 3. All of the events that were identified as mine blasts occurred in areas of active mining. Most of the events that were identified as earthquakes are in areas with the highest natural seismicity in this region: the southwest coast of Norway and the Mid-Atlantic Ridge. Many of the events that were identified as explosions are in active mining areas, but our case-based approach failed to associate them with a known mine. Several of the offshore clusters are known to be explosions from military exercises. Some of the events are obviously identified incorrectly by the automated system (like the events that were identified as explosions on the Mid-Atlantic Ridge). This example shows how we are able to gain valuable information regarding the performance of a discriminant (or set of discrimi-

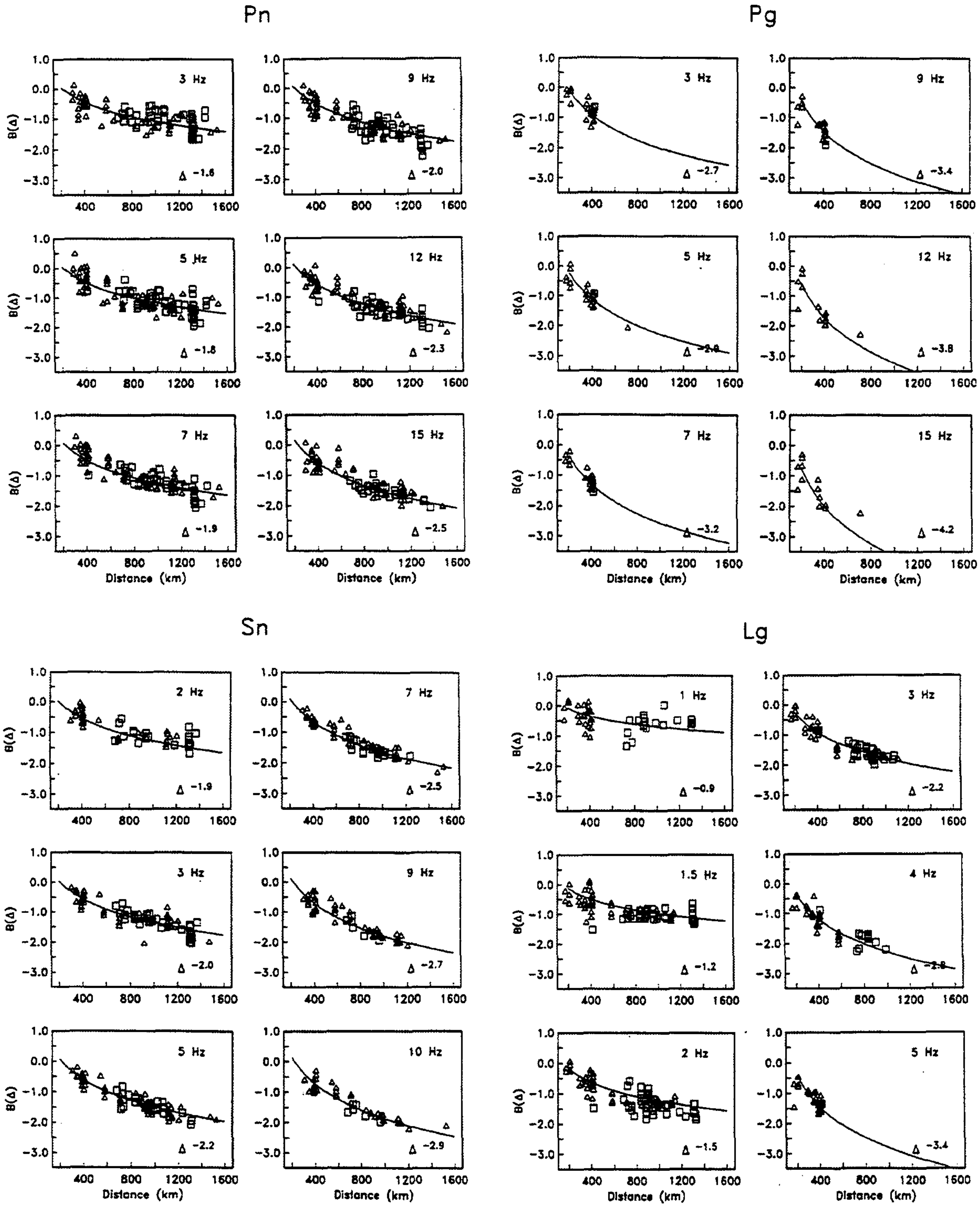

Figure 2. Attenuation is plotted at six frequencies for Pn, Pg, Sn and Lg. The attenuation is parameterized in terms of a power-law dependence on distance. The exponent, *n(f)*, is modeled with a linear dependence on frequency. The solid curves show the attenuation models derived by generalized inversion. The symbols are used to plot source-corrected data recorded at NORESS and ARCESS.

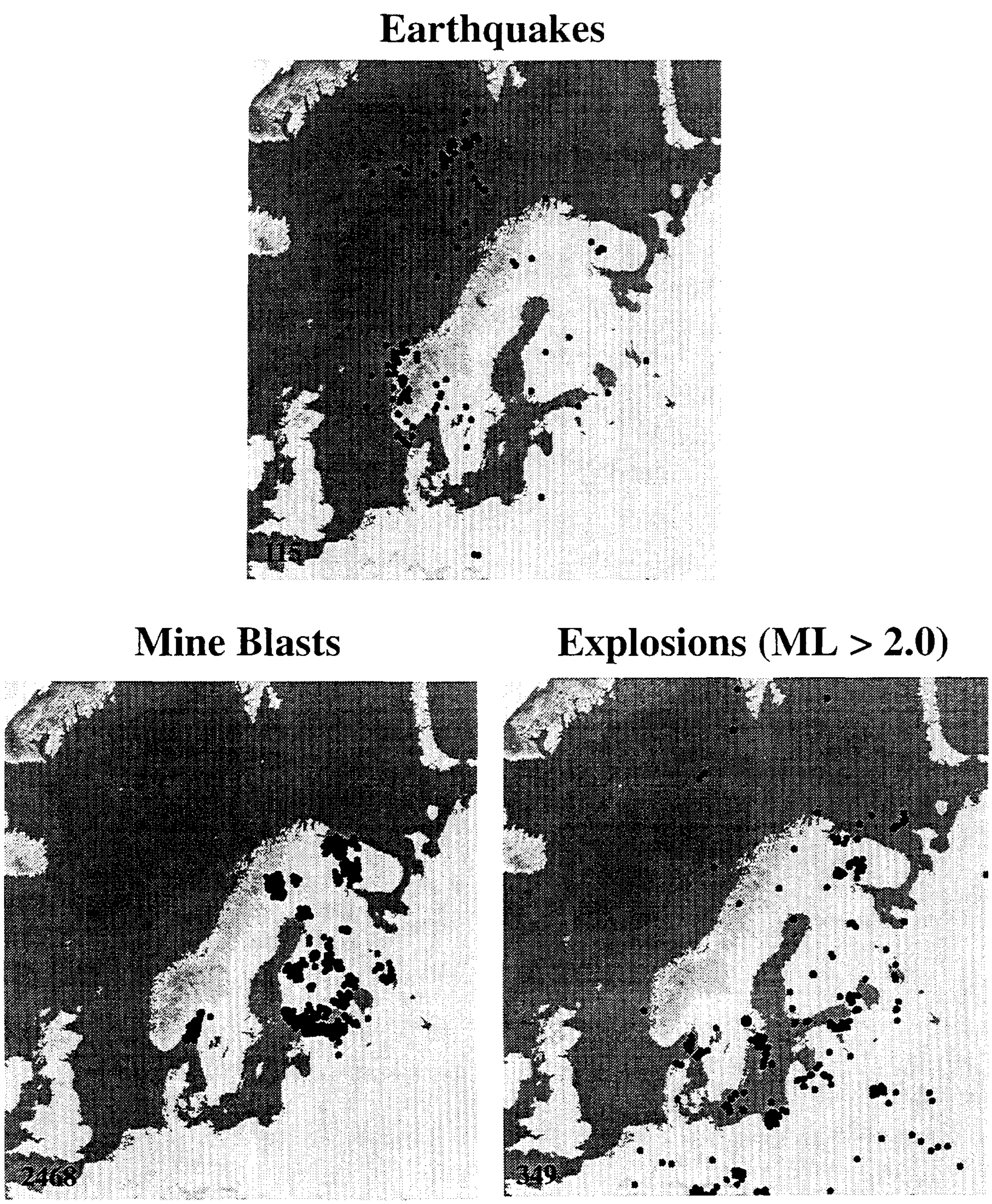

Figure 3. These maps show the location of events that were identified as earthquakes, mine blasts and explosions by the IMS Event Identification System. Ground-truth information is not available for these events, but is it clear that most of the events are identified correctly. The number of events is listed in the lower left corner of each map.

nants) using the general properties of a large number sampling of events without the *ground-truth* information that can be difficult and time-consuming to compile. We plan to use this same approach to evaluate the performance of the Lg/P discriminant.

Distance-Corrected Lg/P Ratios (Task 5.0). The Lg/P ratios will be corrected for distance using the attenuation models. The distance-corrected Lg/P ratios will be compared with the uncorrected ratios to verify that the dependence on distance has been eliminated. For example, Figure 4 shows uncorrected and distance-corrected ratios for events recorded by the high-frequency arrays in northern Europe.

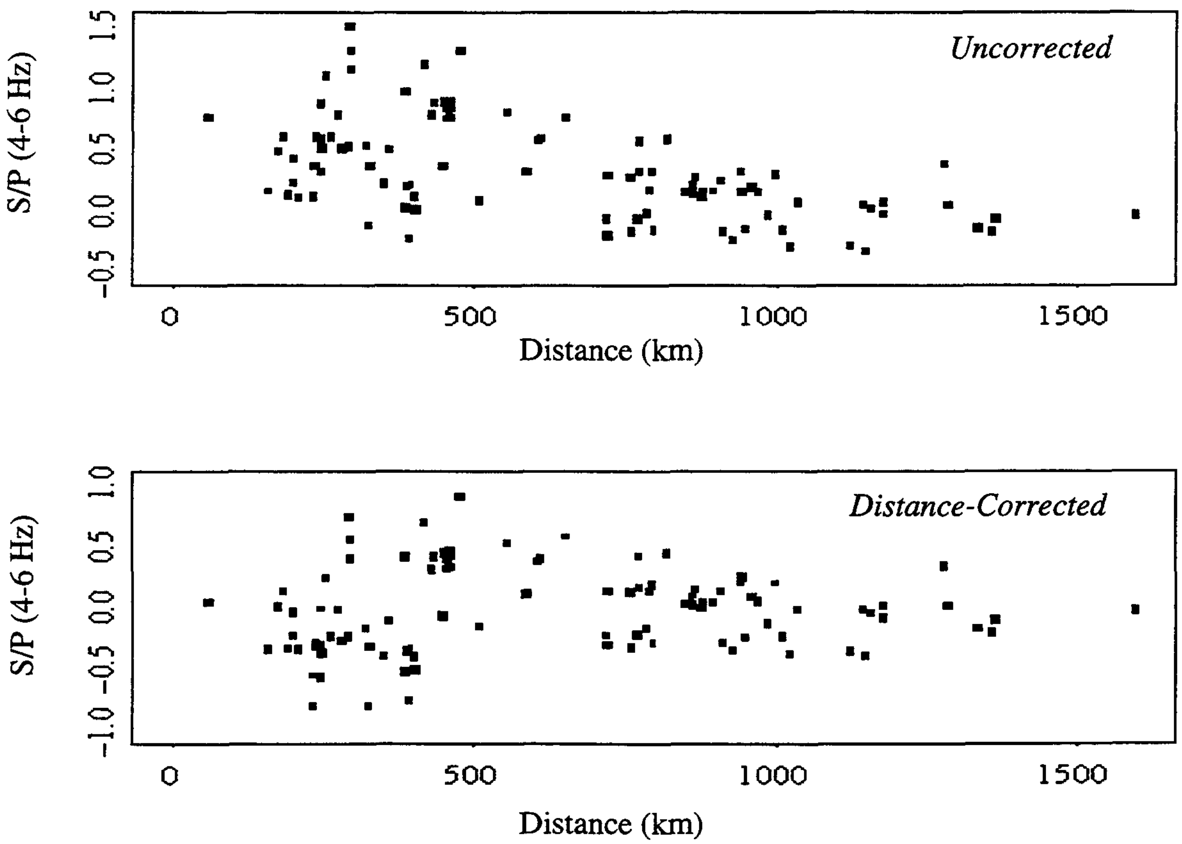

Figure 4. The top panel shows the S/P amplitude ratio in the 4-6 Hz band as a function of distance for events recorded in northern Europe. The bottom panel shows the same events after applying distance corrections developed by *Sereno* [1990].

Identification Accuracy (Task 6.0). The next step is to determine the identification accuracy of the distance-corrected Lg/P discriminant for the data sets described above. We will compare the distributions of the distance-corrected Lg/P amplitude ratios for earthquakes and explosions in our *ground-truth* data set. We have already performed this type of analysis using data from the IMS high-frequency arrays in northern and central Europe. For example, Figure 5 shows the distribution of the distance-corrected *Largest-S/First-P* ratio for earthquakes and explosions recorded by the NORESS, ARCESS, and FINESA arrays in northern Europe, and by the GERESS array in central Europe. The identifications of the events in northern Europe are from the University of

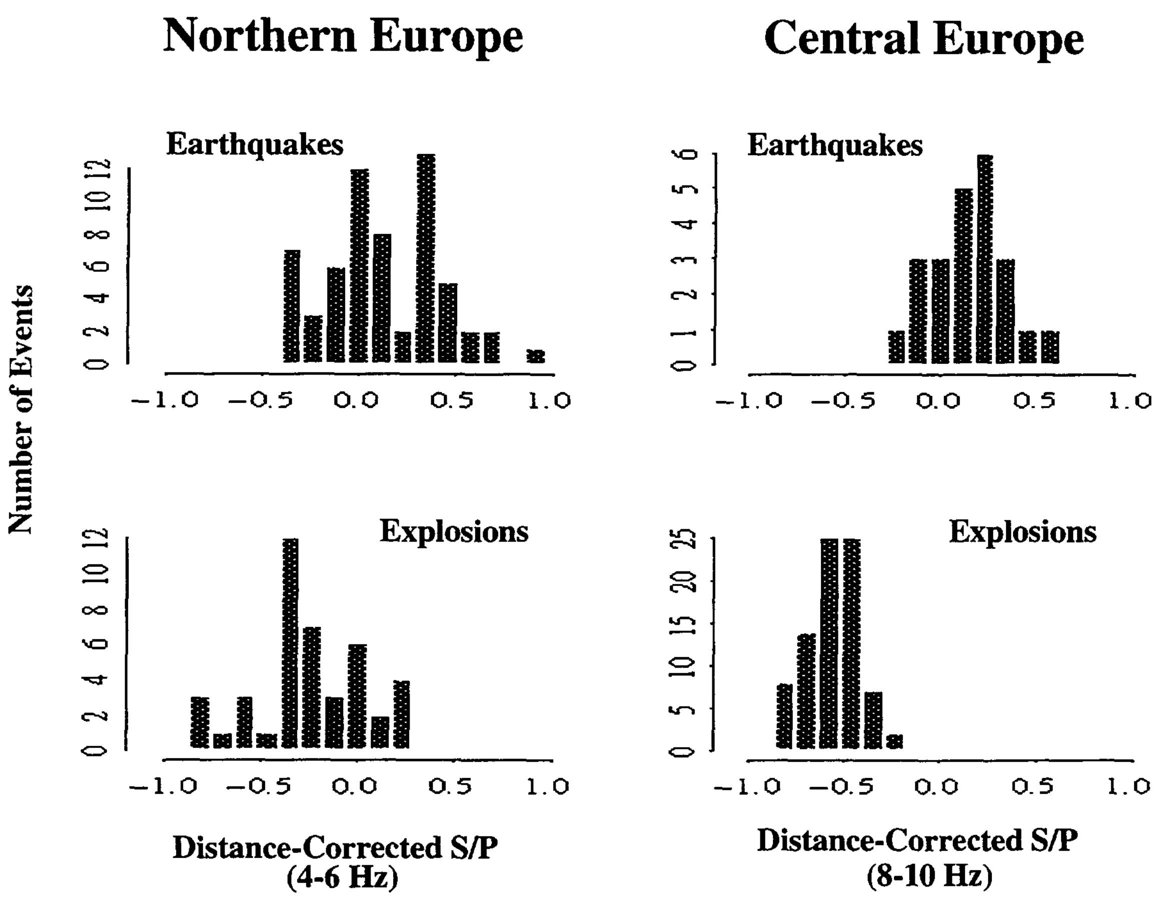

Figure 5. Distance-corrected *Largest-S/First-P* ratios are plotted for earthquakes and explosions in northern Europe (4-6 Hz) and Central Europe (8-10 Hz).

Helsinki and from the *ground-truth* event identification data set developed by *Grant et al.* [1993]. The earthquakes are primarily from the west coast of Norway (near Bergen and Steigen), and on the Mid-Atlantic Ridge. The mining explosions are in the Kola Peninsula, northern Sweden, Finland, St. Petersburg and Estonia. Many of the events in central Europe were also identified in the *ground-truth* database at the Center for Monitoring Research (CMR). They include mining explosions and earthquakes in Vogtland, Germany [*Wuster*, 1993], presumed mining explosions in Austria about 175 km south of GERESS [H. P. Harjes, personal communication], and mining-induced tremors in Lubin, Poland [*Grant et al.*, 1993].

The distance-corrected *Largest-S/First-P* amplitude ratio is higher for earthquakes than for explosions recorded at GERESS in the 8-10 Hz band. *Baumgardt et al.* [1992] previously found that the Lg/P ratio in this band was successful for identifying events in Vogtland, Germany, and we showed that it could be extrapolated to other source regions by applying distance corrections. The Lg/P amplitude ratio does not appear to work as well for events in northern Europe (Figure 5). We found the best discrimination for these data was provided by ratios in the 4-6 Hz band. It is likely that a multivariate approach that combines results from several frequency bands will provide better results in these cases. We will investigate these and other alternatives for deriving a composite identification from Lg/P ratios.

Sensitivity to Attenuation Models (Task 7.0). The sensitivity of the distance-corrected Lg/P discriminant to the accuracy of the attenuation model will directly address the issue of the transportability of this discriminant to uncalibrated regions. We plan to evaluate the effectiveness of the discriminant at each station when distance corrections derived from data recorded at other stations are used. The final result will be an estimate of the identification accuracy of the Lg/P discriminant at each station as a function of the attenuation model.

Regionalization (Task 8.0). This task is to generalize the distance-corrected Lg/P discriminant in terms of geologic and tectonic environment. Like the previous task, it addresses the issue of transportability to uncalibrated regions. First, we will group the data by tectonic province [e.g., *Jordan*, 1981]. Next, we will derive new attenuation models for each province using the method described in earlier Sections. The average attenuation models for each province will be used to compute new distance-corrected Lg/P ratios. The identification accuracy for each province will be compared to the results when station-specific attenuation models were used.

REFERENCES

Baumgardt, D., and G. Young, Regional seismic waveform discriminants and case-based event identification using regional arrays, *Bull. Seismol. Soc. Am.*, *80*, 1874-1892, 1990.

Baumgardt, D., J. Carney, M. Maxson and S. Carter, Evaluation of regional seismic discriminants using the Intelligent Seismic Event Identification System, Tech. Rep. *SAS-TR-93-38*, ENSCO, Inc., Springfield, Virginia, 96 pp., 1992.

Bennett, J., B. Barker, K. McLaughlin, and J. Murphy, Regional discrimination of quarry blasts, earthquakes, and underground nuclear explosions, Final Rep. *GL-TR-89-0114*, 146 pp., 1989. ADA223148

Bennett, J., A. Campanella, J. Scheimer, and J. Murphy, Demonstration of regional discrimination of Eurasian seismic events using observations at Soviet IRIS and CDSN stations, Final Rep. *PL-TR-92-2090*, 122 pp., 1992. ADA253275

Bennett, J., and J. Murphy, Analysis of seismic discrimination capabilities using regional data from western United States events, *Bull. Seismol. Soc. Am.*, *76*, 1069-1086, 1986.

Bennett, J., J. Scheimer, A. Campanella, and J. Murphy, Seismic characteristics of rockbursts for use in discrimination, Sci. Rep. *PL-TR-93-2059*, 89 pp., 1993. ADA266063

Blandford, R., Seismic discrimination problems at regional distances, in *Identification of Seismic Sources - Earthquake or Nuclear Explosion*, E. S. Husebye and S. Mykkeltveit (Ed.), D. Reidel Publishing Co., Dordrecht, The Netherlands, 695-740, 1981.

Brune, J., Tectonic stress and the spectra of seismic shear waves from earthquakes, *J. Geophys. Res.*, *75*, 4997-5009, 1970.

Brune, J., Correction to tectonic stress and the spectra of seismic shear waves from earthquakes, *J. Geophys. Res.*, *76*, 5002, 1971.

Chan, W., R. Baumstark, and R. Cessaro, Spectral discrimination between explosions and earthquakes in central Eurasia, Tech. Rep. *GL-TR-90-0217*, 38 pp., 1990. ADA230048

Chun, K., R. Kokoski, and G. West, High-frequency Pn attenuation in the Canadian Shield, *Bull. Seismol. Soc. Am.*, *79*, 1039-1053, 1989.

Dysart, P., and J. Pulli, Regional seismic event classification at the NORESS array: seismological measurements and the use of trained neural networks, *Bull. Seismol. Soc. Am.*, *80*, 1910-1933, 1990.

Grant, L., F. Ryall, and J. Coyne, CSS ground-truth database: update and case study, Proceedings of the 15th Annual Seismic Research Symposium, *PL-TR-93-2160*, 114-120, 1993. ADA271458

Gupta, I., and J. Burnetti, An investigation of discriminants for events in Western USSR based on regional phases recorded at station Kabul, *Bull. Seismol. Soc. Am., 71*, 263-274, 1981.

Jordan, T., Global tectonic regionalization for seismological data analysis, *Bull. Seismol. Soc. Am., 71*, 1131-1141, 1981.

Lynnes, C., and R. Baumstark, Phase and spectral ratio discrimination in North America, Tech. Rep. *PL-TR-91-2212(II)*, 68 pp., 1991. ADA246673

Mueller, R., and J. Murphy, Seismic characteristics of underground nuclear detonations, *Bull. Seismol. Soc. Am., 61*, 1675-1692, 1971.

Murphy, J., and J. Bennett, A discrimination analysis of short-period regional seismic data recorded at Tonto Forest Observatory, *Bull. Seismol. Soc. Am., 72*, 1351-1366, 1982.

Nuttli, O., On the attenuation of Lg waves in western and central Asia and their use as a discriminant between earthquakes and explosions, *Bull. Seismol. Soc. Am., 71*, 249-261, 1981.

Pomeroy, P., W. Best, and T. McEvilly, Test ban treaty verification with regional data - a review, *Bull. Seismol. Soc. Am., 72*, S89-S129, 1982.

Sereno, T., Attenuation of regional seismic phases in Fennoscandia and estimates of arrival time and azimuth uncertainty using data recorded by regional arrays, Tech. Rep. *SAIC-90/1472*, 115 pp., 1990.

Sereno, T., and J. Given, Pn attenuation for a spherically symmetric earth model, *Geophys. Res. Lett., 17*, 1141-1144, 1990.

Sereno, T. and D. Wahl, A fuzzy logic approach to regional seismic event identification: application to the Novaya Zemlya event on 31 December 1992, Tech. Rep. *SAIC-93/1156*, 24 pp., 1993.

Taylor, S., M. Denny, E. Vergino, and R. Glaser, Regional discrimination between NTS explosions and western United States earthquakes at regional distances, *Bull. Seismol. Soc. Am., 79*, 1142-1176, 1989.

Willis, D., J. DeNoyer, and J. Wilson, Differentiation of earthquakes and underground nuclear explosions on the basis of amplitude characteristics, *Bull. Seismol. Soc. Am., 53*, 979-987, 1963.

Wuster, J., Discrimination of chemical explosions and earthquakes in central Europe - a case study, *Bull. Seismol. Soc. Am., 83*, 1184-1212, 1993.